

SUSY EVENT GENERATORS FOR LINEAR COLLIDERS

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ABSTRACT

The status of event generators for SUSY processes at future Linear Colliders is briefly reviewed.

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1 Introduction

Parton shower Monte Carlo programs, reviewed by Sjöstrand in the previous talk,¹ are important tools for relating perturbative QCD cross sections to experiment. They also make possible more realistic predictions of the potential for future accelerators to study new physics. SUSY at the TeV mass scale is a well motivated extension of Standard Model. A Monte Carlo approach is needed not only to incorporate properly the effects of QCD but also to handle efficiently the many possible chains of decays. Rather detailed treatments of SUSY are now included in three parton shower Monte Carlo programs:

- ISAJET 7.44,² which incorporates ISASUSY by Baer and Tata;
- PYTHIA 6.1,³ which incorporates SPYTHIA by Mrenna;
- HERWIG 6.1,⁴ which takes part of its treatment of SUSY from ISAJET but adds especially R -parity violation.

This talk describes the physics assumptions made in these event generators. It also discusses a few recent developments, such as the incorporation of matrix elements in ISAJET.

2 Minimal Supersymmetric Standard Model

The starting point for all three SUSY generators is the Minimal Supersymmetric Standard Model (MSSM), that is, the SUSY model with the same gauge group as the Standard Model and the minimal particle content. Each chiral $f_{L,R}$ has a scalar partner $\tilde{f}_{L,R}$, and each gauge boson has a spin-1/2 gaugino partner. There are also two Higgs doublets with spin-1/2 Higgsino partners.

The most general such model allows weak scale proton decay. The simplest solution is to impose symmetry under R -parity, where $R = (-1)^{3(B-L)+2S}$. If R is conserved, then SUSY particles produced in pairs and the lightest SUSY particle (LSP) is stable. It is also possible to avoid proton decay by assuming only B or L conservation. The R -violating couplings are Higgs-like, and some but not all of them must be small.⁵ If they are all small, then the only effect of R violation is to allow the LSP to decay, e.g., $\tilde{\chi}_1^0 \rightarrow qqq$, $\tilde{\chi}_1^0 \rightarrow \ell^+\ell^-\nu$, or $\tilde{\chi}_1^0 \rightarrow q\bar{q}\ell$. Larger couplings would also affect other SUSY decays; so far this has been incorporated only in HERWIG.

SUSY must of course be broken. It is possible to add gauge-invariant masses for all the SUSY particles by hand, but at the cost of 105 (or more) new parameters. Presumably these masses should be generated by some sort of spontaneous symmetry breaking. This seems to be impossible using only the MSSM, so one must introduce a hidden sector to break SUSY at a mass-squared scale F and communicate that breaking to the MSSM at a scale M . In supergravity (SUGRA) models, $M \sim M_{\text{Planck}} = (8\pi G_N)^{-1/2} = 2.4 \times 10^{18} \text{ GeV}$ so $F \sim 10^{11} \text{ GeV}$. In Gauge Mediated SUSY Breaking (GMSB) models, the communication is via Standard Model gauge interactions, and M and F are much smaller. This can give a light ($M_{\tilde{G}} \ll 1 \text{ GeV}$) gravitino into which all other SUSY particles decay.

Electroweak symmetry is broken through the Higgs mechanism, leaving five physical Higgs bosons, h, H, A, H^\pm . The gauginos and Higgsinos then mix to give four neutralinos $\tilde{\chi}_i^0$ and two charginos $\tilde{\chi}_i^\pm$. In most cases, the $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm$ are mainly gauginos, while the heavier states have Higgs-like couplings. The scalar fermions also mix, especially for the third generation.

A random choice of the 105 MSSM parameters will produce flavor changing neutral currents and CP violation. These can be avoided by assuming that all phases and flavor mixings are absent. This produces what is called in ISAJET the MSSM parameter set: $M_{\tilde{g}}, \mu, M_A, \tan\beta, M_{Q_1}, M_{d_R}, M_{u_R}, M_{L_1}, M_{e_R}, M_{Q_3}, M_{b_R}, M_{t_R}, M_{L_3}, M_{\tau_R}, A_t, A_b, A_\tau, M_{Q_2}, M_{s_R}, M_{c_R}, M_{L_2}, M_{\mu_R}, M_1$, and M_2 . This is a plausible starting point but has no good theoretical justification.

More tractable parameter sets can be obtained by assuming some sort of universality. If all scalar and all gaugino masses are taken to be degenerate at the GUT scale, then one obtains the minimal SUGRA model. Electroweak symmetry breaking is driven by the large top Yukawa coupling, leading to a four parameters: $m_0, m_{1/2}, A_0$, and $\tan\beta = v_u/v_d$, plus $\text{sgn}\mu = \pm 1$. This model is incorporated using a numerical solution to the renormalization group equations in ISAJET and HERWIG and an analytic approximation in PYTHIA. Recently optional additional parameters have been added to ISAJET so that one can study deviations from it.

An alternative is the minimal GMSB model, in which the messenger sector contains $N_5 \ 5 + \bar{5}$ multiplets of $SU(5)$. There are again just four parameters, the messenger scale M , $\Lambda = F/M$, N_5 , and $\tan\beta$. Gaugino masses are $\propto \alpha\Lambda N_5$, while scalar squared masses are $\propto \alpha^2\Lambda^2 N_5$, where $\Lambda = F/M$. The gravitino mass, or rather the lifetime for gravitino decays, is also a parameter. ISAJET also incorporates a few additional GMSB parameters.

3 SUGRA with $\tan\beta \gg 1$

If $\tan\beta$ is much larger than one, then effects such as $\tilde{b}_L - \tilde{b}_R$ and $\tilde{\tau}_L - \tilde{\tau}_R$ mixing become important. This has been properly included in ISAJET since version 7.32. The most important effect is to increase the splitting of the third generation masses. In particular, the $\tilde{\tau}_1$ can become light, so that the only two-body gaugino decay modes may be $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1^\pm \tau^\mp$ and $\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}^\pm \nu_\tau$. These branching ratios may therefore be greater than 99%, as can be seen in Figure 1.⁶

A limited amount of work has been done on such cases for the LHC.⁷ While measurements are possible, they are clearly quite difficult. Measurements at a linear

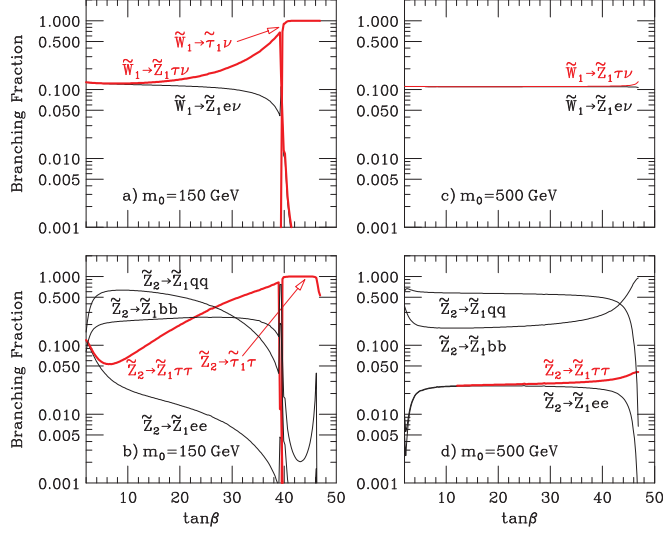


Figure 1: Gaugino branching ratios vs. $\tan\beta$ in the minimal SUGRA model.

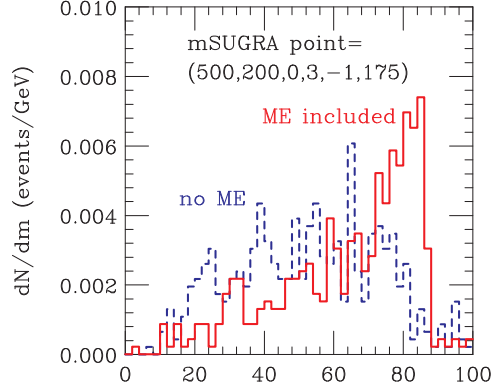


Figure 2: Dilepton mass distribution with (solid) and without (dotted) matrix element.

collider may be easier, at least relatively. E.g., one might measure masses using a threshold scan rather than from τ 's hadronic decays. This deserves more study.

4 Matrix Elements in SUSY Decays

Three-body decays are often important for SUSY. While matrix elements have always been included in the calculation of branching ratios, they have mostly been ignored in the generation of events.

The newest version of ISAJET incorporates matrix elements for decays of the form $\tilde{A} \rightarrow \tilde{B} f \bar{f}$. One does not want to duplicate all the code used to calculate branching ratios inside the event loop. However, the most general matrix element

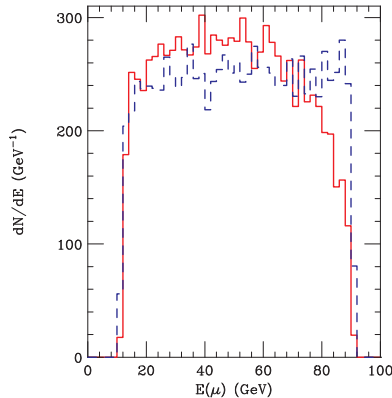


Figure 3: Muon energy distribution with (solid) and without (dashed) bremsstrahlung and beamsstrahlung.

has only spin-0 poles in the $\tilde{B}f$ and $\tilde{B}\bar{f}$ channels and spin-0 and spin-1 poles in the $f\bar{f}$ channel. The strategy is to save the relevant masses and couplings when calculating the branching ratios and then to reconstruct the matrix element with a single generic routine. The same strategy should work for HERWIG and PYTHIA.

The effect can be quite significant, as seen from the dilepton mass distribution from $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow \ell \nu \tilde{\chi}_1^0 \ell \tilde{\chi}_1^0$ at the Tevatron shown in Figure 2. Nogiri and Yamada⁸ have also emphasised the importance of including matrix elements. Incorporating spin correlations in a general way is more difficult and has not been attempted.

5 ISAJET Bremsstrahlung/Beamsstrahlung

Bremsstrahlung has been included in ISAJET 7.44 using the Fadin-Kuraev e^- distribution function. Beamsstrahlung has also been implemented using the formalism of Chen, et al.⁹ The user must specify Υ and σ_z . Both have significant effects on visible endpoint distributions, e.g., for $e^+e^- \rightarrow \tilde{\mu}^+ \tilde{\mu}^-$, as can be seen from Figure 3.

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